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Depolarization remote sensing by orthogonality breaking

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Abstract

A new concept devoted to sensing the depolarization strength of materials from a single measurement is proposed and successfully validated on a variety of samples. It relies on the measurement of the orthogonality breaking between two orthogonal states of polarization after interaction with the material to be characterized. The two fields orthogonality being preserved after propagation in birefringent media, this concept is shown to be perfectly suited to depolarization remote sensing through fibers, opening the way to real time depolarization endoscopy.

The interaction of the electromagnetic radiation with natural objects has long been the subject of intensive investigations. Most significant advances in terms of physics understanding and applications are in the microwave domain where the amplitude, the phase and the polarization of the field are routinely used, for instance, in long range sensing systems in order to optimize the extracted information from a given scene [1–4]. Conversely, in the optical domain where common sensors are based on quadratic detection, it is usual to cope with the intensity of the backscattered field. In particular in the case of polarimetric imaging, the determination of the state of polarization of the backscattered light involves the Stokes vector whose four elements correspond to measured intensities [5]. A rigorous analysis of the depolarization nature of a given material implies the determination of its Mueller matrix which linearly couples the backscattered Stokes vector to the illumination Stokes vector, thus requiring 16 measurements [6]. Consequently, this common approach is very stringent since it implies a perfect control of the polarization states of the emitted light as well as a precise projection of the backscattered electric field on the four analysis states of polarization. Moreover, this approach is very restrictive in terms of wavelength tuning and applies only to free space propagation forbidding the use of fibers as part of the polarimetric apparatus.

Although some techniques have been recently proposed in the context of biomedical imaging to perform polarimetric measurements through fibers [7, 8], they are again based on the same principle, namely, shining the object with a diversity of states of polarization and analyzing the backscattered signal with a polarization sensitive detector. In Ref. [7], it is demonstrated that the degree of polarization of a given material can be recovered statistically but to the expense of a large and time consuming number of realizations. In this context, we felt that, as far as the depolarization strength (degree of polarization) of a material is the parameter of interest, the usual approaches are not optimal from an experimental point of view. Indeed, as far as one parameter has to be determined, it should be possible in principle to retrieve it from a single measurement. More importantly, if such a single measurement is achievable experimentally, then it automatically solves the problem of polarimetric remote sensing through fibers. In this Letter we propose to revisit the way of performing depolarization measurements in the optical domain using the optical electric field rather than its intensity. To this aim, we propose a novel polarimetric sensing modality which involves the concept of polarization orthogonality breaking. We show theoretically and

confirm experimentally that this new sensing modality is able to provide the depolarization nature of a material and is by essence insensitive to propagation through fibers. These results thus open the way for high-sensitivity real time endoscopic polarimetric imaging, a very promising tool in biomedical optics for *in vivo* and *in situ* marker-free diagnosis [7, 8]. Although limited so far to free-space measurements, polarization sensitive imaging techniques have indeed proven efficient in the diagnosis of a number of skin pathologies [9–12] or precancerous lesions [12–14].

In a majority of applications, including biomedical diagnosis, polarimetric imaging end-users are mainly interested in revealing polarization contrasts which may not appear on standard intensity images [5, 9–15]. In such context, characterizing the full Mueller matrix or the Stokes vector \mathbf{S} provides superfluous information, as evidenced by the variety of simplified polarimetric imaging designs available [9, 15–17]. In most applications, a relevant contrast parameter to consider is the degree of polarization (DOP) $\mathcal{P} = [1 - 4 \det(\Gamma_{\text{out}})/\text{tr}(\Gamma_{\text{out}})^2]^{1/2}$, with $\Gamma_{\text{out}} = \langle \mathbf{E}_{\text{out}} \mathbf{E}_{\text{out}}^\dagger \rangle$ denoting the polarization matrix of the backscattered light which can be bijectively derived from \mathbf{S} [5], with $\langle \rangle$ denoting statistical (ensemble) average. However, a majority of materials can be considered as purely depolarizing [15, 18], i.e., their Mueller matrix is well approximated by a diagonal matrix of rank 2. In that case, \mathcal{P} can be evaluated from only two intensity measurements through orthogonal polarizers $\mathcal{P} = (I_{//} - I_{\perp})/(I_{//} + I_{\perp})$, when the samples are enlightened with linearly polarized light. In general, the action of a purely depolarizing material on an incident state of polarization $|\mathbf{E}_{\text{in}}\rangle$ can be phenomenologically modeled by a partial projection of the incident state onto the orthogonal polarization direction denoted $|\mathbf{E}_{\text{in}}^\perp\rangle$, i.e.,

$$|\mathbf{E}_{\text{out}}\rangle = \sqrt{\rho}(|\mathbf{E}_{\text{in}}\rangle + \alpha|\mathbf{E}_{\text{in}}^\perp\rangle)$$

, where

$$\alpha = \frac{\sqrt{1 - \mathcal{P}}}{\sqrt{1 + \mathcal{P}}}$$

. Using Jones matrix formalism, such relation reads

$$\Gamma_{\text{in}} = \langle |\mathbf{E}_{\text{in}}\rangle \langle \mathbf{E}_{\text{in}}| \rangle$$

$$|\mathbf{E}_{\text{out}}\rangle = \mathbf{J}_{\mathbf{m}}|\mathbf{E}_{\text{in}}\rangle = \sqrt{\rho}[\mathbf{R}_{|\mathbf{E}_{\text{in}}\rangle}]^\dagger \begin{pmatrix} 1 & \alpha \\ \alpha & 1 \end{pmatrix} \mathbf{R}_{|\mathbf{E}_{\text{in}}\rangle}|\mathbf{E}_{\text{in}}\rangle, \quad (1)$$

where the unitary matrix $\mathbf{R}_{|\mathbf{E}_{\text{in}}\rangle} \in SU(2)$ corresponds to the generalized polarization rotation mapping the transverse field eigen basis $\{|\mathbf{e}_1\rangle, |\mathbf{e}_2\rangle\} \triangleq \{|\mathbf{e}_{\text{in}}\rangle, |\mathbf{e}_{\text{in}}^\perp\rangle\}$ into the standard linear transverse field basis $\{|\mathbf{e}_X\rangle, |\mathbf{e}_Y\rangle\}$.

$$\mathbf{M} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & P & 0 & 0 \\ 0 & 0 & P & 0 \\ 0 & 0 & 0 & P \end{pmatrix}$$

From Eq.(1), it is seen that a non-null off-diagonal term α leads to a superposition of the two orthogonal states of the electromagnetic field. Assuming that these two eigenstates $|\mathbf{e}_1\rangle$ and $|\mathbf{e}_2\rangle$ are non-degenerate, that is, they have two distinct eigenfrequencies, a coherence oscillation at the eigenfrequencies difference is expected, as illustrated in Fig.1.(a). Moreover, the amplitude of the coherence oscillation is directly linked to the depolarization value \mathcal{P} through α . Thus, the depolarization strength of a given material can be recovered from the way this material breaks the orthogonality of a properly prepared state of the electromagnetic field. To illustrate this property, let us consider a light source emitting two distinct frequencies along two orthogonal polarization states

$$|\mathbf{E}_{\text{in}}(\mathbf{r}, t)\rangle = \frac{E_0}{\sqrt{2}} e^{-2j\pi\nu_1 t} \left[|\mathbf{e}_1\rangle + e^{-2j\pi\Delta\nu t} |\mathbf{e}_2\rangle \right], \quad (2)$$

with $\psi_k(\mathbf{r}, t) = M_k(\mathbf{r}) e^{-2j\pi\nu_k t}$. Such state is a physical implementation of a non-quantum entangled state [19, 20]. For the sake of simplicity, we consider the case of orthogonal states of equal intensities, which can be shown to be the best compromise in terms of detection performance, and we restrict ourselves to the case of plane waves, i.e., $M_k(\mathbf{r}) = 1$. In the most general case, the eigenstates $|\mathbf{e}_1\rangle$ and $|\mathbf{e}_2\rangle$ can be elliptical with orthogonal azimuth directions and equal ellipticity. The polarization matrix Γ_{in} of such illumination field can be decomposed in two terms $\Gamma_{\text{in}} = \Gamma^0 + \Gamma^{\Delta\nu} e^{-j2\pi\Delta\nu t}$. The first term Γ^0 accounts for the continuous part of second-order correlations between the field transverse components, whereas $\Gamma^{\Delta\nu}$ describes interference terms, oscillating at the beat note frequency $\Delta\nu = \nu_2 - \nu_1$. From the above definitions, one can easily derive the input field continuous intensity $I_{\text{in}}^0 = \text{tr}(\Gamma^0) = |E_0|^2$, while the amplitude of the beat note intensity modulation $I_{\text{in}}^{\Delta\nu} = \text{tr}(\Gamma^{\Delta\nu}) = 0$, since the two orthogonal input states do not interfere.

When such a field interacts with an object characterized by its Jones matrix \mathbf{J} , the value of the beat note intensity modulation of the resulting field $I_{\text{out}}^{\Delta\nu} = \text{tr}(\mathbf{J}\Gamma^{\Delta\nu}\mathbf{J}^\dagger)$ provides a

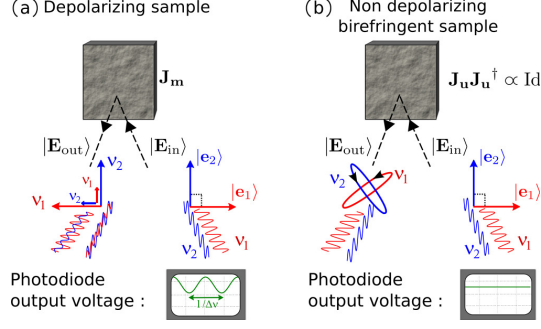


FIG. 1. Principle of Depolarization Sensing by Orthogonality Breaking (DSOB).

direct information on the depolarization properties of the object. As illustrated in Fig.1.(a), the loss of orthogonality induced by the interaction with a depolarizing sample gives rise to an interference intensity component oscillating at a frequency $\Delta\nu$ and whose amplitude is bijectively related to the material depolarization strength. If the depolarizing sample is described by \mathbf{J}_m given in Eq.(1), one indeed has

$$C_{\text{out}}^{\Delta\nu/0} \triangleq \frac{P_{\text{out}}^{\Delta\nu}}{P_{\text{out}}^0} = \frac{4\alpha^2}{(1 + \alpha^2)^2} = 1 - \mathcal{P}^2. \quad (3)$$

The DOP of the sample can thus be directly retrieved from a single measurement of the beat note optical power $P_{\text{out}}^{\Delta\nu}$ (normalized by the cw optical power P_{out}^0). This quantity can be measured with a heterodyne detection, thus enabling fast ($< 1 \mu\text{s}$ for $\Delta\nu = 1 \text{ GHz}$), highly-sensitive depolarization measurements.

On the other hand, non-depolarizing media (isotropic, birefringent or optically active media) are characterized by unitary trace-preserving Jones matrices. Such a matrix verifies $\mathbf{J}_u \mathbf{J}_u^\dagger \propto \text{Id}$, where Id is the identity matrix, and thus $I_{\text{out}}^{\Delta\nu} = 0$, demonstrating that orthogonality between the two illumination states is preserved when light propagates through such media. This property, illustrated in Fig.1.(b), is valid provided no significant dispersion appears between frequencies ν_1 and ν_2 . This is very unlikely to occur in practice since $\Delta\nu$ will not exceed tens of GHz for the beat note to be detectable on a photodetector. A consequence of this result is that the Depolarization Sensing by Orthogonality Breaking (DSOB) technique proposed in this Letter is in essence insensitive to birefringence and polarization rotation, thus enabling remote sensing through optical fibers, in which stress/torsion-induced birefringences are usually highly detrimental to usual polarimetric measurements [7].

In order to experimentally illustrate and validate the DSOB principle, we have implemented the setup depicted in Fig.2.(a). In this setup, the probe field state is prepared using

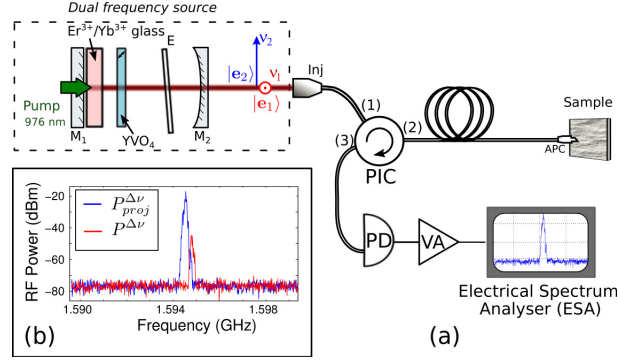


FIG. 2. (a) Schematic representation of the depolarization remote-sensing setup. Dashed box: description of the Er,Yb;Glass laser producing the two orthogonally polarized and frequency shifted fields. (b) Measurement of the RF contrast obtained on a fibred mirror ($\Delta\nu = 1.254$ GHz).

a single laser source which inherently produces the two orthogonal polarization states with shifted frequencies. This laser consists of an Er,Yb;Glass 4-cm-long external cavity laser emitting at 1550 nm. Single longitudinal mode oscillation is obtained with an intracavity 40- μm -thick silica etalon whose both sides are coated for 40% reflection at 1550 nm. Moreover, a 500- μm -thick YVO₄ crystal, cut at 45° of its optical axis, is inserted into the laser cavity in order to, at the same time, define two linear polarization eigenstates, lift the frequency degeneracy, and finally ensure a slight polarization walk-off (50 μm) in the active medium. This walk-off reduces the nonlinear coupling between the two eigenstates [21] leading to robust and simultaneous oscillation of the two polarization eigenstates. The active medium is diode pumped at 976 nm. Lateral positioning of the pump beam enables equalization between the two eigenstates intensities. By slightly tilting the etalon and the YVO₄ crystal, it is possible to set the frequency difference $\Delta\nu = \nu_2 - \nu_1$ to a value compatible with the detection setup, namely within the radio-frequency (RF) range, i.e., $\Delta\nu < 2$ GHz. With this configuration, the laser provides an output power of 1.8 mW with a pump power of approximately 130 mW.

We emphasize that the depolarization measurement concept we propose here is expected to be well suited for remote sensing. In order to validate this expectation, the laser output is injected into, and guided along, a 2 m-long single-mode optical fiber (SMF28) before shining the sample. The backscattered light is back-propagated into the same fiber, extracted with a polarization-insensitive circulator (PIC) and directed on a high-band pass (16 GHz) photodiode (PD). The detected RF signal is amplified with a high-gain (60 dB,

2 GHz cut-off frequency) voltage amplifier and analyzed on a 40 GHz band pass electrical spectrum analyzer (ESA). It is worth noticing that this measurement setup does not require any component to be inserted at the distal fiber-end and may thus be directly adapted to commercial endoscopes. More importantly, no polarizing or birefringent elements are needed, and the spectral range of the setup is therefore only limited by the source, the photodiode and the fiber spectral excursions. As a consequence, the DSOB technique could easily provide spectrally resolved polarimetric measurements, which can be interesting for material characterization or biomedical diagnosis [22].

To calibrate and test this experimental setup, we first evaluated the maximum “polarimetric orthogonality contrast” available with such a measurement scheme. This was done by comparing the residual beat note power $P^{\Delta\nu}$ (caused by imperfect orthogonality between the polarization states) to the maximum beat note power available $P_{proj}^{\Delta\nu}$, obtained by inserting a polarizer (transmission $T_p = 85\%$) at a 45° angle with respect to the illumination polarization directions at the laser output. This contrast was derived from the corresponding spectra analyzed around frequency $\Delta\nu$ on the ESA, as illustrated in Fig.2.(b). After injection into the fiber, we measured a high contrast of -34 ± 1 dB. After propagation through a 20 km-long SMF, a reduced but still high contrast of -25 ± 1 dB was measured, showing that orthogonality is fairly maintained during propagation over tens of kilometers. It was also observed that the circulator was rather detrimental to orthogonality, since a contrast of -28 ± 1 dB has been measured at the output port (2) of this component, and -27 ± 1 dB at the output port (3) after reflection on a fibred mirror. At this level, it is interesting to note that such setup providing a measurement dynamics of 25 dB makes it possible to measure values of \mathcal{P} up to 99.5 % (respectively 99.95 % with a 30 dB dynamics). The new DSOB technique addressed in this Letter may therefore be a very efficient tool when slight depolarization contrasts have to be characterized.

Further calibration was also conducted by using the setup of Fig.2.(a) and a fibred collimator to illuminate a rotating polarizer (axis $\theta_0 = 32^\circ$) followed by a mirror. The polarimetric contrast of the light back-propagated into the fiber was analyzed on the spectrum analyzer for various orientations θ of the polarizer. The obtained results are plotted in Fig. 3 and are in fair agreement with our theoretical predictions showing that in the experimental

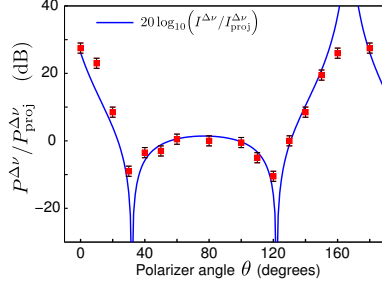


FIG. 3. Polarimetric orthogonality contrast measured with the setup of Fig.2.(a) on a rotating polarizer and mirror. The RF powers were measured with an ESA.

configuration considered, one has

$$\frac{I^{\Delta\nu}}{I_{proj}^{\Delta\nu}} = \left| \frac{2 \left[\sin(2(\theta - \theta_0)) + K_0 \right]}{T_p \left[1 + K_0 + \sin(2(\theta - \theta_0)) \right]} \right| \quad (4)$$

with $K_0 = 0.3\%$ denoting the amount of intensity reflected at the fiber/collimator end.

Once calibrated, the setup of Fig.2.(a) was tested on a variety of materials (see inset of Fig.4.(b)) to validate experimentally the DSOB technique. To match endoscopic applications requirements, we considered a challenging experimental configuration where the materials under investigation were placed in the vicinity of the APC fiber-end connector without any collimation optics. In such conditions, a very weak proportion of the illumination optical power was backscattered into the fiber mode and propagated to the detector: $\simeq 10 \mu\text{W}$ on a metallic adhesive sample (sample 3) and only $\simeq 0.7 \mu\text{W}$ on a diffusive paper sheet (sample 5). However, the heterodyne detection scheme involved in DSOB enables a very high sensitivity after amplification of the detected signal and analysis on the ESA. A natural improvement of this setup would be using a lock-in detection to measure precisely the output electrical power at frequency $\Delta\nu$. Indeed, the ESA used here for the proof of concept is not required and could be advantageously replaced by a demodulation circuit since the frequency of interest $\Delta\nu$ is known.

The results obtained are reported in Fig.4. It can first be checked in Fig.4.(a) that the relative beat note optical power is low ($C_{out}^{\Delta\nu/0} = -22.5 \pm 1 \text{ dB}$) on a non-depolarizing medium (metal adhesive, $\mathcal{P} = 0.99$), whereas it considerably increases ($C_{out}^{\Delta\nu/0} = -1.5 \pm 1 \text{ dB}$) on a diffusive and depolarizing sample (white paper, $\mathcal{P} = 0.11$). For the sake of experimental convenience, $C_{out}^{\Delta\nu/0}$ was determined here by normalizing the RF output power $P_{out}^{\Delta\nu}$ (blue curves) by $P_{out,proj}^{\Delta\nu}$ (green curves), i.e., the RF power obtained with projected polarization

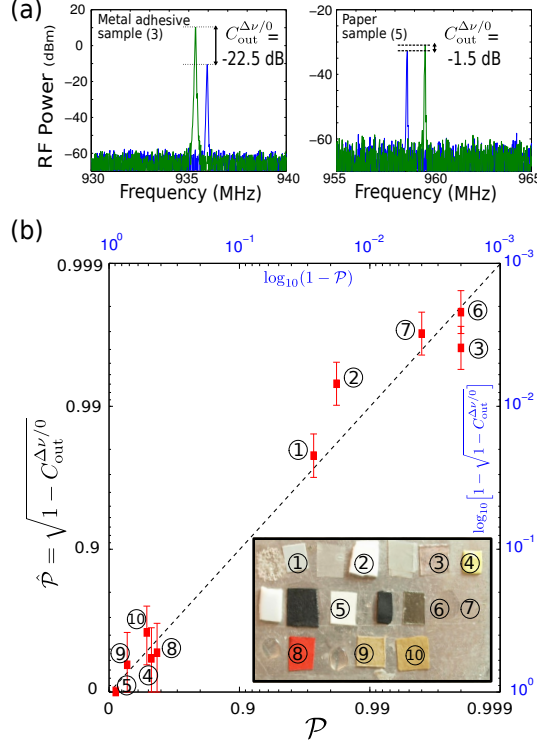


FIG. 4. (a) Evaluation of the RF polarimetric contrast on a non depolarizing (left) and a depolarizing (right) sample with $\Delta\nu \simeq 950$ MHz. (b) The DOP estimated ($\hat{\mathcal{P}}$) from RF beat note power measurement is in fair agreement with the DOP of the samples characterized at $\lambda = 1.55 \mu\text{m}$ with a standard free-space Stokes measurement setup

states at the laser output, which provides the overall optical power backscattered by the sample (up to a factor $T_p/2$). Then, on a variety of ten samples with distinct depolarization properties, the relative beat note optical power $p_{\text{out}}^{\Delta\nu}$ was measured and injected in Eq.(3) to provide an estimation of the DOP. The estimated values of $\hat{\mathcal{P}}$ are plotted in Fig.4.(b) and are in good agreement with the DOP of the samples, characterized independently with standard Stokes free-space measurements performed at $1.55 \mu\text{m}$. These experimental results validate the concept of remote depolarization sensing by polarization orthogonality breaking, as well as the DSOB setup proposed.

In this Letter, we introduced a new polarimetric measurement technique, based on the concept of orthogonality breaking, and allowing one to measure the depolarization strength of a material from a single measurement in a few tens of milliseconds. In addition, the DSOB technique is *per se* insensitive to propagation through a fiber and is easily implemented without requiring any specific component at the distal end of the fiber, nor in front

of the detector, thus paving the way for depolarization remote-sensing of biological tissues with conventional endoscopes. Based on a heterodyne detection setup, the proposed method is highly sensitive and therefore perfectly suited for biomedical applications where biological tissues are often slightly depolarizing and prone to photodamage. Improving the source control and implementing a demodulation circuit is a perspective to this work, before applying the DSOB technique to real-time polarization-sensitive endoscopic imaging on samples of biological interest. On a wider scope, the DSOB principle may find applications in a number of fields, such as remote sensing and radar, material characterization, fibre-based sensors or any other physical measurement resorting to the orthogonality breaking principle.

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